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PROGRESS IN MANAGEMENT OF SEDIMENT BYPASSING AT COASTAL INLETS: NATURAL BYPASSING, WEIR JETTIES, JETTY SPURS, AND ENGINEERING AIDS IN DESIGN

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Maintenance of navigable channels at coastal inlets typically requires sediment bypassing to preserve integrity of the adjacent beaches. Artificial bypassing mimics or preserves the pathways of sediment in the littoral zone and harmonizes the requirement for deepening navigation channels within the context of the natural sediment-sharing system of inlets and beaches. A range of techniques can be applied to perform bypassing. Customary on-demand channel dredging is not always the best solution because sediment shoaling does not necessarily follow a predictable schedule, potentially compromising navigation reliability between allowable dredging windows. If sediment can be directed to a location other than the channel, planning of dredge operations may be optimized and less expensive equipment feasible. A weir jetty system is one such solution. This paper presents progress in understanding of sediment bypassing through analytical prediction and takes a lessons-learned approach to design and modification of weir jetty bypassing systems. Results from recent physical model studies of spur jetties are also discussed with regard to their control on the nearshore current at coastal inlets and how spurs can be designed to alter sediment bypassing.

Keywords: Coastal inlets; sand bypassing; weir jetty; jetty spur.

1. Introduction

Coastal inlets provide a channel for transportation from sea to harbor ports and allow water exchange and renewal necessary for the ecological health of bays and estuaries. In sandy coastal regions, a navigation channel has a tendency to be a

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sink and accumulate sediment moving along the coast and from shallow shoals that flank the inlet. A major engineering effort is often required to remove this sediment from the inlet entrance by dredging the channel and placing the dredged material at an economically feasible and physically appropriate location along the coast, for example, such that it does not readily return to the channel during times of longshore transport reversal.

A central element of coastal inlet maintenance is bypassing of sediment from the inlet region back to the adjacent beaches. Artificial bypassing mimics or preserves the pathways of sediment in the littoral zone and harmonizes the requirement for deepened navigation channels within the context of the natural sediment-sharing system of inlets and beaches. Many coastal inlets have jetty structures that stabilize the location of the navigation channel, protect vessels from waves breaking in shallow water, and reduce channel infilling by sediment. Sediment eventually accumulates on the seaside of these structures and moves around the seaward jetty tips into the navigation channel. Sediment may also pass over a jetty at the shoreward end by either being blown by wind or washed over in a combination of sediment accumulation, elevated water level, and wave run-up during storms. If there is a net movement of sediment along the coast toward the inlet, one side may tend to accumulate sediment (until it then passes by the tip of the jetty into the channel), while the beach down drift is eroded due to sediment blockage. The above description is a simplified representation of the complex movement of coastal sediment, but it is a characteristic pattern at many stabilized inlets.

Several methods and actions have been developed to maintain a deep channel and accommodate the bypassing and handling of sediment at inlets (Bruun, 1978, 1981; Richardson, 1991). Hereafter, such sediment will be assumed to consist primarily of sand (and perhaps gravel), because fine-grained material is not usually placed on beaches. A typical sand bypassing operation involves a mobile dredge that can move to necessary locations within the inlet to clear the shoaled channel and pump or transport the sand to the beach or the nearshore. A problem with the on-demand dredging procedure is that sand that has reached the channel prior to scheduled maintenance dredging may reduce navigation reliability. Weather and environmental windows can limit when the channel is dredged to only a few months a year in some locations. Similarly, the down-drift beach may require sand when a sea-going dredge cannot be scheduled.

As opposed to dredging, "fixed systems" have been designed to intercept the sand before it reaches the channel. South Lake Worth Inlet and Lake Worth Inlet, Florida, have stationary slurry pumping plants operating from platforms on jetties. These systems are designed to intercept sand before it reaches the channel, and then to pump it past the inlet and to the down-drift beach. At Indian River, Delaware, a jet pump has been deployed from a crawler crane to permit some mobility to this "fixed" type bypassing system (Clausner, *et al.*, 1991). Sediment volumes of more than 75,000 cubic meters/year are bypassed from the south jetty fillet to the

down-coast beach. It can be difficult to fully intercept all the sand moving toward an inlet. Natural bypassing of sand movement past the inlet may be facilitated by structure orientation, e.g. overlapping jetties, but interception of the sand by the channel may still occur.

Work conducted in the last 40 years has examined ways to direct the sediment to a location where it may be handled by a small dredge and also minimize interruption of natural bypassing. Examples include the dredging of a deposition basin in the channel itself. This has been done at Carolina Beach, North Carolina (Vallianos, 1970), and at Sebastian Inlet, Florida (Bruun, Mehta, and Johnsson, 1978). Capture of sediment in the lee of an offshore breakwater before reaching the inlet has been implemented at Channel Island, California (Bruun, Mehta, and Jonsson, 1978) and at Ventura Harbor, California (Hughes and Schwichtenberg, 1998).

A prominent example of sediment redirection is the weir jetty system. Several weir-jetty systems have been constructed in the United States, but under limited design guidance, a few have been considered successful. This paper examines selected such inlets and systems and suggests, in some cases, what modification might increase their performance. Also, in certain situations, the use of spurs on the seaside of jetties may prove beneficial in reducing the amount of littoral sediment from entering the navigation channel and in controlling its location for rehandling. These possible engineering actions are first placed in the context of the natural mechanisms of sand bypassing at coastal inlets.

2. Natural Sand Bypassing at Inlets

Mechanisms of natural sand bypassing at inlets were first elucidated in a systematic way by Bruun and Gerritsen (1959, 1960). Bruun (1991) gives an update on the concepts and describes several case studies. These works identified two bypassing modes as (1) bar bypassing, in which sand moves around the inlet along the bypassing bars and ebb-tidal shoal, and (2) tidal bypassing, in which the sediment enters the channel on flood current and exits on the other side of the inlet in the ebb current. Bar bypassing inlets tend to have a large gross longshore sand transport rate (the gross transport rate is equal to the sum of the rates from the left and right sides of the inlet) as compared to tidal prism, whereas tidal bypassing inlets tend to have a larger tidal prism as compared to the gross amount of material transported to the inlet during the course of a year. Bruun and Gerritsen (1959, 1960) noted that bypassing could take place at an inlet in both modes. Gaudiano and Kana (2001) document a third type of natural sand bypassing mode called episodic bypassing, by which sand is transferred downdrift by the collapse of a large portion of the ebb shoal. Episodic bypassing is found at inlets with strong tidal flow as compared to hydrodynamic influence by waves, and the periodicity of the South Carolina inlets studied showed the process to occur about every 7 years, likely triggered by a storm. Inlets at other locations may have longer or shorter cycles of episodic bypassing.

The concepts of Bruun and Gerritsen (1959, 1960) were quantified in a mathematical model called the Reservoir Model (Kraus, 2000a) for Ocean City Inlet and subsequently validated at a number of inlets in the United States (Kraus, 2000b; Militello and Kraus, 2001; Zarillo, Kraus, and Hoek, 2003). This model is based on interpretation of sediment pathways and knowledge of equilibrium values of the volumes of morphologic features of ebb shoals.

As an example of application of the Reservoir Model, Shinnecock Inlet, New York is considered. This inlet has a federal channel maintained to 3 m depth mean lower low water and includes over-dredging to 6 m to form a deposition basin for trapping sand to bypass to the chronically eroding beach on the west side. Predominant longshore transport is to the west, as can be seen from the asymmetrical shape of the bypassing bars and ebb shoal. Morphologic features for this inlet were identified through bathymetric surveys and interpretation of aerial photographs (Fig. 1). Attachment bars (denoted as "A. Bar" in the figure) are locations where sand leaves or enters the beach in the natural bypassing process. Other features are the ebb shoal, flood shoal, channel, and bypassing bars. The Reservoir Model was applied to this inlet for evaluating the flood shoal as a borrow site for bypassing to the

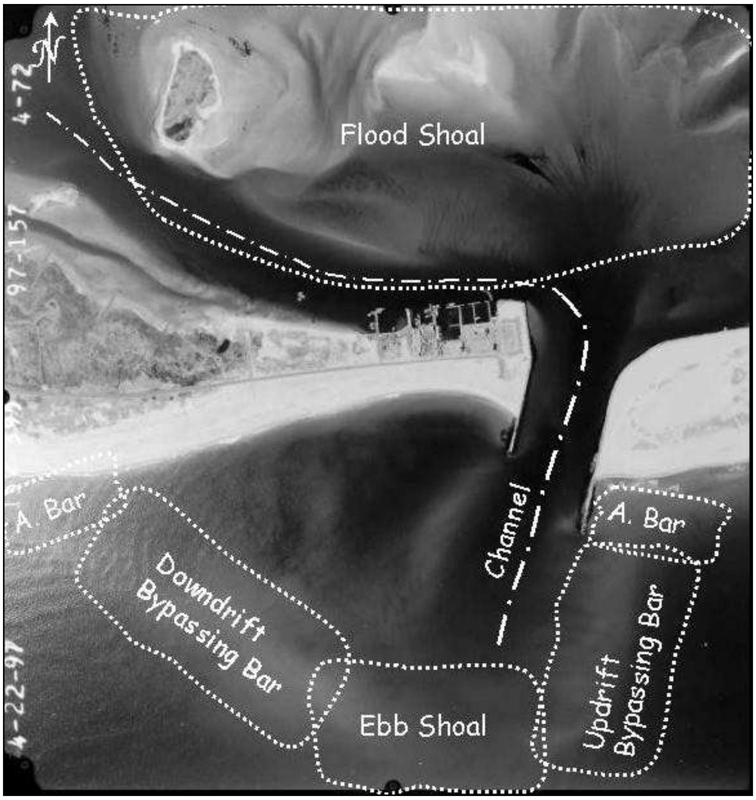


Fig. 1. Morphologic features at Shinnecock Inlet, New York.

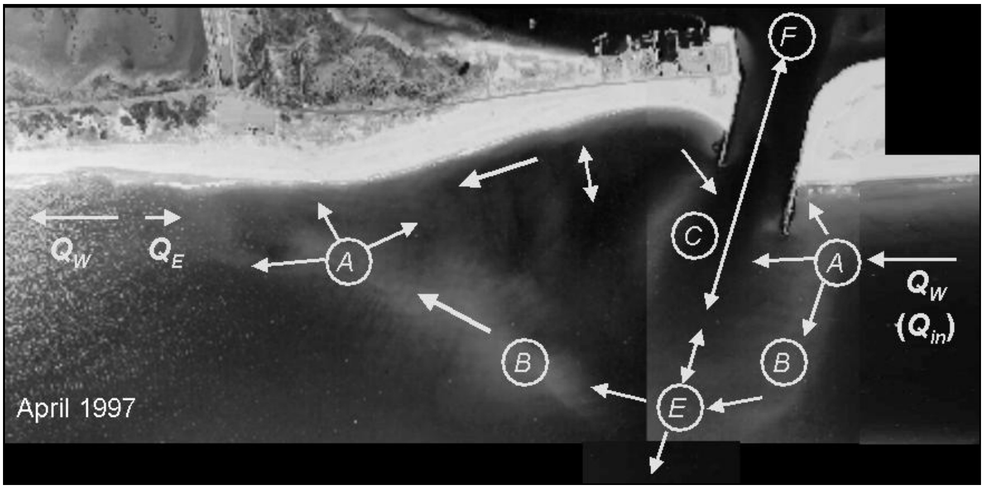


Fig. 2. Interpreted sediment-transport pathways at Shinnecock Inlet.

west beach, as described by Militello and Kraus (2001), which can be consulted for further information. Here, concepts pertaining to natural bypassing are discussed.

Sediment pathways for Shinnecock Inlet were inferred based on inspection of the morphology, dredging history, and numerical modeling of the waves and tidal hydrodynamics (Militello and Kraus, 2001). Sediment transport pathways are drawn in Fig. 2, where the attachment bars (A), bypassing bars (B), channel (C), ebb shoal (D), ebb shoal, (E), and flood shoal are shown, with arrows denoting the interpreted directions of transport for the situation of predominant (westward) transport. The total longshore transport rate to the west Q_W, which serves as the input transport rate Q_{in} for this direction, and the rate directed to the east Q_E are annotated on this figure. Both bar bypassing, such as A to B to E to B to A, and tidal bypassing (A to C to F to E) are represented as conceptually described by Bruun and Gerritsen (1959, 1960).

Mathematical details of the Reservoir Model and project studies have been described elsewhere (Kraus, 2000a, 2000b, 2001; Militello and Kraus, 2001; Zarillo, Kraus, and Hoek, 2003), so only its basis and potential applications are discussed here. Figure 3 shows the concept of the model. It requires identification of morphologic features of an inlet, sediment pathways between them (as illustrated in Fig. 2), and equilibrium values of the features (Kraus, 2001), which are treated analogously to reservoirs. In the model, it is assumed that an individual reservoir can accept and provide sediment to adjacent reservoirs (morphologic features). The amount provided to other features is assumed proportional to the amount (volume) of sediment available and the rate of input. For features with multiple inputs and outgoes, percentages among them must be assigned. The model can then calculate the volume growth of the morphologic features and volumetric rates of natural sand bypassing.

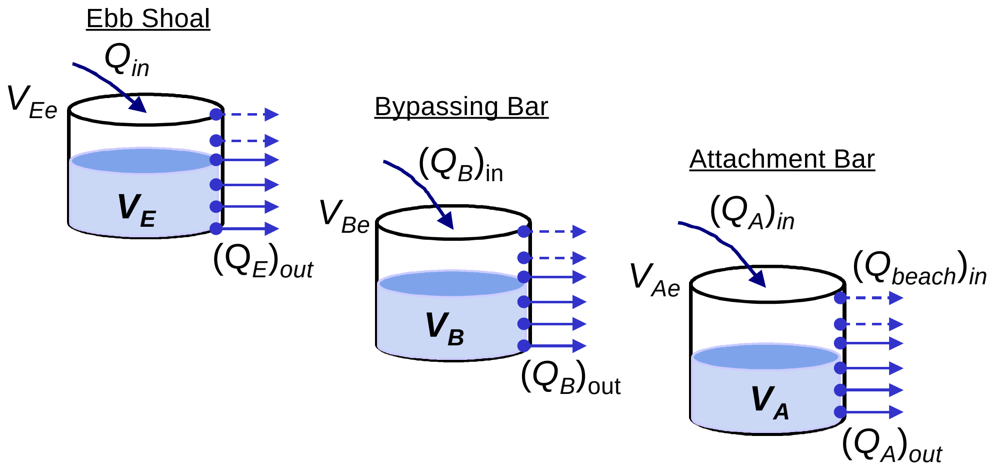


Fig. 3. Concept sketch for reservoir inlet morphology model.

The Reservoir Model has been applied to evaluate the interruption of the natural bypassing rate by mining of the ebb shoal, bypassing bar, and flood shoal. In the United States, ebb shoals are often mined for sediment bypassing (e.g. Cialone and Stauble, 1998). Dredging of channels can also be represented, with placement prescribed to downdrift morphologic features, such as to the adjacent beach. The model shows the adaptation time of the inlet morphologic system toward re-establishment of bypassing rates. Characteristic time scales of adaptation or recovery of the system are calculated, and for smaller inlets, this might be 3–10 years, whereas for larger inlets, the adaptation time can be 10 to 20 years for typical amounts of material dredged for bypassing (50,000–500,000 m^3). The Reservoir Model was applied, for example, to calculate dredging of the deposition basin at Shinnecock Inlet (Militello and Kraus, 2001), which would function similarly to the deposition basin at a weir jetty as discussed next.

3. Weir Jetty Systems

A weir jetty system is one of several methods for bypassing sediment at coastal inlets. Others methods, as described above, include an offshore breakwater, a deposition basin in the channel, a fixed pumping plant, or a jet pump suspended from a crane. Figure 4 shows typical elements of a weir jetty system. The weir section, usually less than about 300 m long, is a depressed region of the jetty that permits waves and the longshore current generated by wind, waves, and tide to transport sediment moving along the coast to enter a deposition basin located in the lee of the weir, thereby reducing the amount of sediment entering the navigation channel. A weir also acts as a breakwater and provides a semi-protected area for dredging the deposition basin.

Another benefit is that the weir allows flood currents to enter the inlet over the weir and through the channel during flood flow with subsequent channeling of ebb

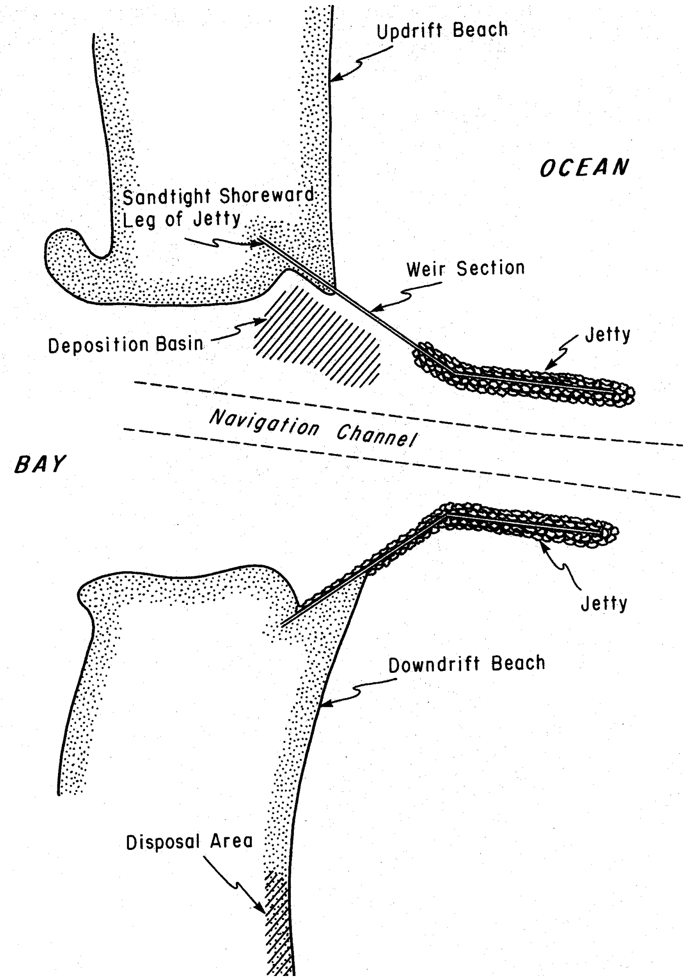


Fig. 4. Typical elements of a weir jetty system.

flows out the navigation channel between the jetties. The flood current is weaker in the navigation channel, relative to the channel ebb current, promoting net seaward sediment flushing. Thus, less sediment enters the bay channels, where it is lost to the beach system if it settles in flood shoals in the bay or contributes additional volume in bay channels that require dredging. A potential benefit for new jetty systems is that the outer tips of the jetties may not need to extend seaward as far as a system without a weir jetty, because seaward sediment transport from the beach along the outside of the jetty is minimized (Seabergh and Lane, 1977). Many variations of this example (Fig. 4) are possible, depending on structure orientation, bathymetry, and presence of bottom features such as shoals and rock reefs. Table 1 lists weir jetty projects in the United States, including length, elevation and orientation of the weir. Some examples will be discussed below.

Table 1. Weir Jetty Costal Inlets in the United States.

Location	Weir Elevation, m, Typically Relative to Mean Low Water	Length of Weir, m	Length of Weir Jetty, m	Orientation of Weir[1], Degrees	Weir Material	Gross Longshore Transport Rate Estimates, cu m/year
Boca Raton, FL	0.0 (N.G.V.D.)	20	North jetty 198	90	Concrete bags	Net rate 91,750 to S
Charleston, SC	−4.0	1,829	4,694 N 5,821 S	70	Rubble mound	—
Colorado River Mouth, TX	0.0	305	East jetty 808	90	Rubble stone	229,400
East Pass Channel, FL	−0.2	305	West jetty 1,478	45	Concrete sheet pile	149,000
Hillsboro Inlet, Fl	Varying +0.2–+1.1	79	North jetty 148	0	Natural rock	91,750
Masonboro, NC	+0.6	335	North jetty 1,109	85	Concrete sheet pile	260,000
Murrells Inlet, SC	+0.7	411	North jetty 1,053	30	Rubble mound	191,000
Perdido Pass, AL/FL	−0.2	305	East jetty 548	45	Concrete sheet pile	149,000
Ponce DeLeon, FL	0.0	457	North jetty 1,234	60	King piles and adjustable concrete beams	535,000
Rudee Inlet, VI	+0.6	138	South jetty 248	90	Timber	460,000
St. Lucie, FL	0.0	274	North jetty 1,211	90	Rubble mound	200,000

1. Angle from general trend of shoreline measured on the channel side.

3.1. *Field examples of weir jetty projects*

This section describes the weir jetties and their performance at selected coastal inlets.

3.1.1. *Hillsboro Inlet, Florida*

Hillsboro Inlet is a natural inlet about 610 m long that had a channel shoaling problem causing navigational difficulty. In 1930, a granite rock jetty was constructed, projecting 79 m southeast from the north shore to an existing rock reef formation. This natural reef varied in elevation from +0.1 m to +1.1 m relative to the mean-low-water datum (tide range about 0.8 metre). In 1952, a 152 m long timber jetty was built on the south side of the channel. A 69 m long breakwater extension was built on the north side of the inlet in 1965. This framed in a weir section, 79 m long (elevation +0.1 m to +1.1 m mlw) between the original jetty and the extension structure (see Fig. 5). This natural weir provided a means for sand to pass into the inlet deposition basin, thus making it the prototype for the weir-jetty concept (Weggel, 1981). Predominant littoral drift is toward the weir, from north to south (University of Florida, 1965). After completing the jetty improvements, the inlet channel was deepened to improve navigation. The deepening included a cut through the existing rock at the mouth of the inlet to a depth of approximately 3.0 m below mean sea level and width of 53 m between the jetties. All inlet improvements were

Fig. 5. Hillsboro Inlet, Florida, was the first sand-bypassing weir jetty system. The design incorporated a natural reef formation for the weir.

completed in November 1965. The shore-parallel weir arrangement proved beneficial due to limited wave action in the deposition basin area behind the weir because of the flat beach slope in front of the weir (Weggel, 1983). This arrangement also provided a means for regular dredging of the basin without exposing the dredge to harsh open-water conditions (Coastal Planning & Engineering, Inc., 1991).

3.1.2. *Masonboro Inlet, North Carolina*

This Inlet has been open continuously since 1733. It migrated southward of its present position and, in 1909, it was located 1,220 m down-beach from its present location. Improvements to stabilize its location, authorized in 1949, included two jetties and an ocean entrance channel between the jetties. The interior channels were dredged in 1957, and in 1959, the ocean navigation channel was dredged with design depth of 4.3 m at mean low water (mlw) and 122 m width at the bottom. This channel shoaled quickly and was reestablished in 1959 (Seabergh, 1976). Continued shoaling in the channel and attendant maintenance dredging problems led to the

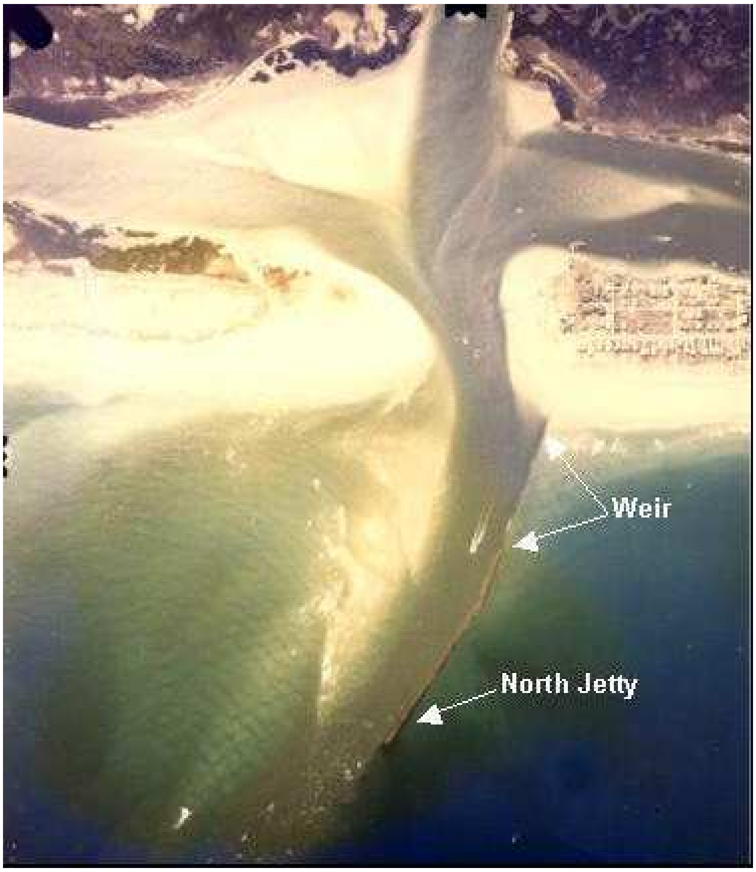


Fig. 6. Masonboro Inlet, North Carolina, 7 years after construction of the north weir jetty (1972).

construction of the two previously authorized jetties. Limitation in funding dictated that the north jetty, due to its location on the apparent up-drift side of the inlet, be constructed first (Fig. 6) and was completed in 1965. The north jetty was designed with a weir to aid sand bypassing. This was the first time that a sand weir-bypassing feature had been incorporated into a US Army Corps of Engineers (USACE) jetty design. The overall length of the jetty was 1,109 m, with a 530 m long concrete sheet pile on the landward side of the jetty forming the weir and 579 m of rubble-mound jetty concstructed seaward. The crest elevation of the shoreward 183 m of the sheet pile varied from +3.7 m to +0.61 m, mlw, with 335 m long weir section at a crest elevation of +0.61 m, mlw, approximately at mean tide level. The rubble-mound portion of the north jetty had design crest elevations varying from +1.8 m to 2.4 m, mlw.

In 1969, because of the migration of the navigation channel toward the north jetty, a stone apron was placed to provide toe protection along the rubble-mound section of the jetty. This migration was not caused by the weir, but was a typical channel response to a single-jettied system (Kieslich, 1981) where the ebb shoal collapses in towards the single jetty, forcing the channel against the structure. Construction of the south jetty, built of quarry stone and concrete sheet pile to make it

Fig. 7. Masonboro Inlet, North Carolina, after construction of the south jetty.

sand tight to a length of 1,052 m, began in July 1978 and was completed in August 1980. Figure 7 shows the dual-jetty project. The bulbous right shoulder of the inlet formed after construction of the south jetty, when wave activity was reduced in that location. Previously, much sediment would enter the interior Banks Channel after passing over the weir (interior channel at top of Fig. 7) and settle there to be dredged for beach nourishment of Wrightsville Beach. Thus the deposition basin region was not capturing sediment as designed because the sand typically moved over the weir at the swash zone. This sand eventually formed a spit and required vessels entering the inlet to make sharp turns in strong crosscurrents to remain in the navigation channel. However, by using the sand spit as an extended deposition basin area, the USACE Wilmington District has only had to dredge the deposition area every 3 to 4 years, and the dredging also keeps the spit from further encroaching into the navigation channel [Government Accounting Office (GAO) 2002].

3.1.3. *Ponce De Leon Inlet, Florida*

Prior to 1968, Ponce De Leon Inlet had functioned as a natural passage through the barrier islands separating the Atlantic Ocean from Halifax River and Indian River North. The inlet became recognized as difficult and dangerous to navigate with controlling depths over the ebb shoal of typically 1.2 to 1.8 m (King *et al.*, 1999). During 1968–1972, two rubble-mound jetties were constructed to provide safe passage via a 4.6 m deep by 61 m wide dredged channel. The north and south jetty have overall lengths of 1,234 m and 1,242 m respectively. A 549 m long weir of king piles and adjustable concrete beams were constructed along the north jetty. The weir section consisted of a 91 m landward length at +1.2 m mlw elevation, and seaward a 457 m length at 0.0 mlw elevation. An impoundment basin to entrap material

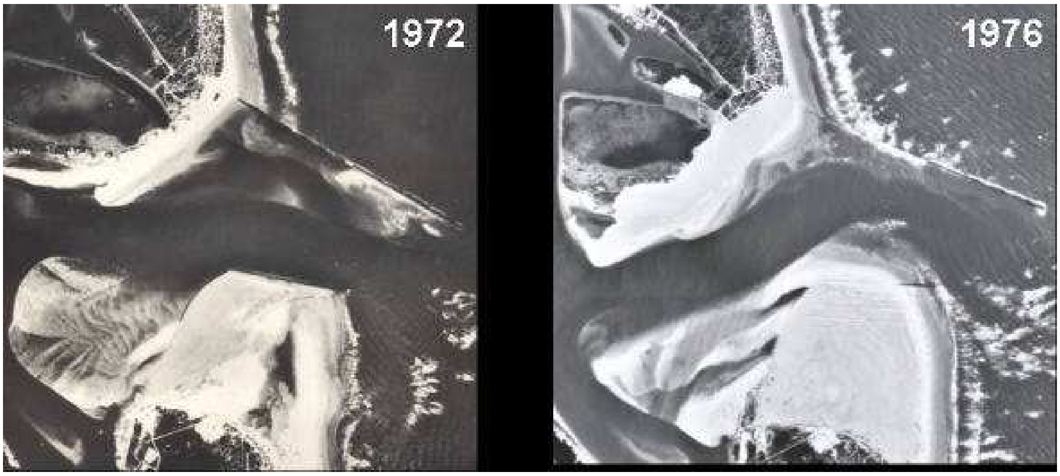


Fig. 8. Ponce de Leon Inlet, Florida. Construction completed in 1972. Weir is located on the top (north) jetty. Note spit development and channel migration into deposition basin in 1976.

passing over the weir in the north jetty was dredged between the weir section and the entrance channel (Taylor and Yanez, 1994). In 1972, one year after north jetty construction was completed, riprap was placed along the south side of the area adjacent to the weir section to provide scour protection. Figure 8 shows the inlet in 1972 with a sand spit migrating over the weir along the swash zone towards the interior channel. By 1976, the spit has grown, and the inlet channel had reoriented and was cutting through the deposition basin adjacent to the weir.

In 1984, the weir was closed because the impoundment basin was ineffective, and navigation through the inlet was difficult due to the increased wave heights and crosscurrents in the entrance (Harkins, Puckette, and Dorrell, 1997). The north jetty continued to experience scour, while the shoreline just south of and adjacent to the north jetty continued to recede westward. According to interpretations made by Stauble *et al.* (1999), the channel is returning to pre-jetty orientation with the weir closed.

3.1.4. *Murrells Inlet, South Carolina*

Murrells Inlet had migrated up and down the coast over a range of 2 km during the last century. To stabilize the inlet location, in 1977, two armor stone jetties (Fig. 9)

Fig. 9. Murrells Inlet, South Carolina, just after completion of project construction in 1981.

were constructed at a cost of $7.4 million. The north jetty, 1,053 m long, consists of a 171 m long shoreward jetty trunk; a 411 m long armor stone weir section (crest elevation +0.7 m mlw, set at mean tide level) (Weggel, 1981); a 503 m long seaward jetty trunk; and a 46 m long head section. The north jetty (with the exception of the weir section) and the south jetty are built to an elevation of 2.7 m above mlw. The south jetty, 1,012 m long, consists of a 966 m long trunk and a 46 m long head section. Also, a 2.4 m wide fishing walkway was constructed on the crest of the jetty to an elevation +3 m mlw. Sand dikes composed of dredged material tied the jetty roots into the existing dune lines. The seaward parallel sections of the jetties were 183 m apart with an entrance channel 91 m wide and 3.7 m deep at mlw between them. The deposition basin was dredged to a depth of 6.1 m mlw with a capacity of 459,000 cubic meters. It was dredged adjacent to the low weir section of the north jetty (Perry, Seabergh, and Lane, 1978). More than a million cubic yards of sand from these two dredging projects were pumped to adjacent beaches.

The dominant direction of longshore transport was assumed to be southerly when the inlet project was designed (Douglass, 1987), and the weir section was placed on the north jetty. As of 1985, the jetties had no history of damage or repair and appeared to be functioning properly (Sargent, 1988). Spit growth into the bay along the inlet shoulder illustrates the usual path of sediment transport coming over a weir. Predominant waves and longshore current move fine sand along the swash zone, generating spit growth around the north shoulder of the inlet. Sediment enters the shoreward portion of the deposition basin. The ebb current also carries sediment from the edge of the spit entering the interior navigation channel into the bayward end of the deposition basin, as can be noted in Fig. 9. According to the USACE Charleston District, the project has performed better than expected because planned 3-year maintenance dredging has been needed only once since the project was built. District staff states the channel through the inlet has been kept open primarily by the flushing action of the current flowing through the jetties (GAO, 2002). The shoreline adjacent to the weir has receded an average of 0.6 m/year since 1981.

3.1.5. *Mouth of the Colorado River, Texas*

The mouth of the Colorado River tended to skew to the west (left in Fig. 10), most likely a response of the channel to spit growth from the east. As part of navigational improvements dating 1988–1990, two rubble-mound jetties were constructed at the mouth of the Colorado River, providing protection for the 4.6 m deep, 61 m wide entrance channel, that discharges to the Gulf of Mexico. The west jetty is 442 m long, and the east jetty, which contains a rubble-mound weir, is 808 m long. The east jetty weir section begins 125 m from the landward end and extends 305 m seaward. The crown elevations of the weir section and remaining jetty sections are 0.0 m and +2.4 m, mlw, respectively. The seaward ends of the east and west jetties

Fig. 10. Mouth of Colorado River, Texas, January 2001.

are about 549 m apart. The jetty design incorporated an impoundment basin on the channel side of the north jetty to trap littoral drift material passing over the weir (Sargent and Bottin, 1989). The basin was initially dredged to hold 2-year supply of 459,000 cubic meters (Lin, Kraus, and Barcak, 2002).

After constructing the jetties and weir, the position of the channel became stable, and vessels could exit heading into the typical waves as opposed to meeting them broadside as would occur without the jetties. This weir jetty and impoundment basin were constructed to accommodate the anticipated increased deposition and have not functioned satisfactorily (Kraus, Lin, and Barcak, 2003), because the amount of sand flowing over the weir has been greater than expected, and a significant portion was deposited in the navigation channel rather than into the deposition basin (GAO, 2002). Once again the sediment pathway, as noted for other weir jetty projects, once passing over the weir, is along the shore or swash zone towards the channel. However, modifications to improve the functioning in the system are soon to be incorporated. The first modification is to construct an impoundment basin training structure to function as a groin in halting encroachment of the east spit to the channel and to direct westward moving longshore sediment transport into the basin (Kraus, Lin and Barcak, 2003). Raising of the weir to mean sea level is also under consideration.

3.2. *Weir jetty design based on prototype and modeling experience*

Many lessons can be extracted from the examination of weir jetty systems that have been built in the latter part of the 20th century. Problems are varied and include scour along the structure, tidal currents migrating through the deposition basin, and sediment bypassing the basin near the shoreline, as examples. In most cases, the problems can be solved by some modification or adjustment to the project ("project tuning").

3.2.1. *Deposition basin location and size*

At many weir jetty sites, the shoreward edge of the deposition basin was placed at about the location of the low-water line of the adjacent beach. Murrells Inlet (Fig. 9) is an example. Under normal conditions, sediment transport is along the inner surf zone at the landward end of the weir, and sediment moves along the shore landward of the basin, creating a spit that elongates toward the interior channel or into the main navigation channel. Flood flow, together with waves and wave-generated longshore currents over the weir, develop the spit feature and curve it around the inlet shoulder. The ebb current shears off the sediment from the wrapping spit, and sediment moves into the channel-side of the basin (early ebb flow was aligned with the basin while currents exited over the weir, which shut off once the mid-tide level of the weir is reached); then, some sediment is carried seaward along the navigation channel to the ebb shoal (Fig. 9). The interior spit was formed during construction of the jetties before the south jetty was built, and greater wave energy wrapped the spit tighter into the interior channel.

The ebb current directed toward the deposition basin is expected to decrease as the tide level falls. Because the weir elevation at Murrells Inlet is at mean tide level, ebb flows are concentrated in the navigation channel during the later stages of ebb flow. To prevent sediment from passing over the weir and bypassing the deposition basin on the shoreward side once inside the weir, a possible solution would be to move the deposition basin landward relative to the weir, or in the case of an existing weir, cover a portion of the landward edge of the weir with stone, creating an offset with respect to the basin. Figure 11 illustrates this setback of the basin. Also shown in Fig. 11 is that, for more energetic wave conditions, suspended sediment could pass over the more seaward portion of the weir and settle in the deposition basin. The location of maximum sediment transport over the weir is at the location of wave breaking on the seaward side of the weir. This figure was derived from laboratory studies (Seabergh, 1983). For small or typical waves, sediment would wrap landward and into the basin. Because of greater basin depth, the sediment will be constrained to the basin. As the deposition basin fills and becomes shallower, there will be a tendency to develop a sediment pathway that will extend to the rear of the basin and out toward the bay and interior channels. Regular basin dredging can alleviate this potential problem. If the dredging schedule is irregular or the transport episodic, a

revetment wall can be constructed at the back of the basin for confinement. Problems with a confining wall may relate to potential scour if a wall terminates adjacent to the navigation channel, and it could also be a hazard to navigation.

Deposition basin size is usually based on how often dredging can be scheduled and the estimated longshore sediment transport rate. The optimal design of a basin and associated structures is intended to capture the net longshore transport volume, as described below. (Such capture of sediment assumes the basin is placed on the side of the inlet where the greater amount of longshore sediment volume originates.) Capturing only the net longshore transport volume will facilitate reduced sediment handling. The recommended procedure is to design for some amount greater than the yearly net, but less than the yearly transport directed toward the basin. This value may then be doubled to provide reserve if, for some reason, a dredging cycle is missed. Ways to achieve capture of only the net transport are described in the next section.

3.2.2. *Design with respect to net long-shore sediment transport*

Ideally, a weir jetty system should provide a deposition basin that can contain one to two years of the net longshore transport. In order to capture only the net longshore transport rather than the total right-to-left transport (use Fig. 11 as a reference), the

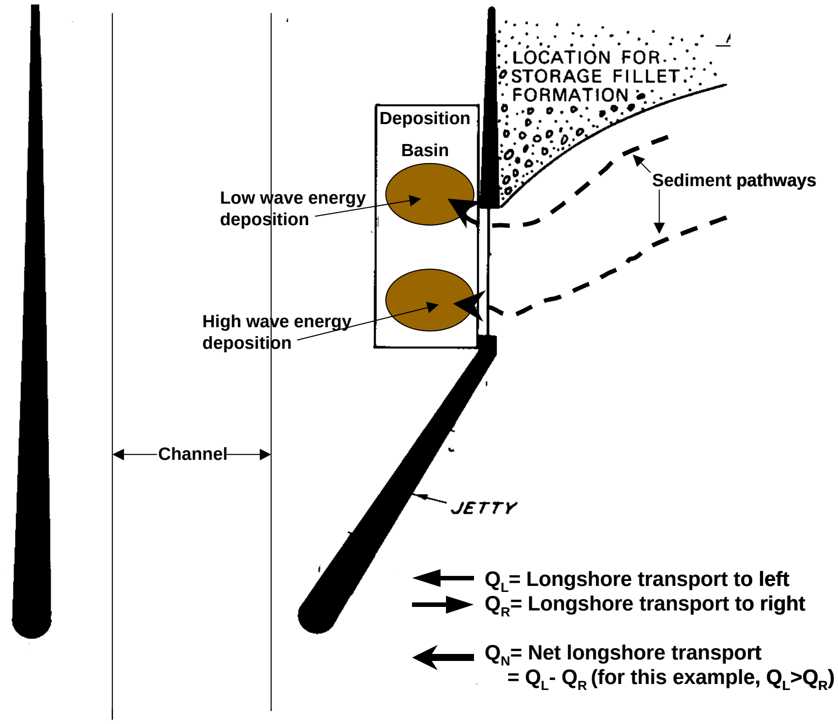


Fig. 11. Sediment pathways over weir for low and high wave conditions.

weir should be less transmissive than if the longshore transport were unidirectional (right-to-left) and in this case it is desirable to capture all the sediment in the basin. To accomplish this, the difference between the right-to-left sediment and net sediment volumes must be temporarily stored where it is available to be moved back during left-to-right movement. In other words, a portion of the right-to-left movement must be prevented from entering the deposition basin. Offsetting the weir seaward of the original shoreline may be beneficial with regard to the creation of a temporary fillet region that fills when the longshore sediment transport is directed from right to left in Fig. 11. After the fillet has grown to the shoreward edge of the weir, sediment will begin entering the deposition basin. Capturing the net transport minimizes sediment-handling costs. If right-side jetty orientation will permit wave approach to move sediment out of the fillet region back up-coast, this is possible. If the right-side jetty creates a large shadow zone so that sediment does not move left to right out of the fillet, a possible up-coast groin may hold sediment, and so it is available for transport to the right. Figure 12 illustrates this approach.

As mentioned in the previous paragraph, designing weir sections to capture and bypass only the net transport is reasonable guidance if there is a relatively greater volume of sediment approaching from the predominant direction. In the case of balanced left-to-right and right-to-left transport, it may not be desirable to construct a weir jetty, unless sediment is moving seaward along the jetty to the tips of the jetty. Then, to reduce the strength of sediment pathways to the jetty, a weir might be constructed. However, other methods may be employed to prevent sediment from entering the channel, such as jetty spurs on the seaward side of the jetty, or groin

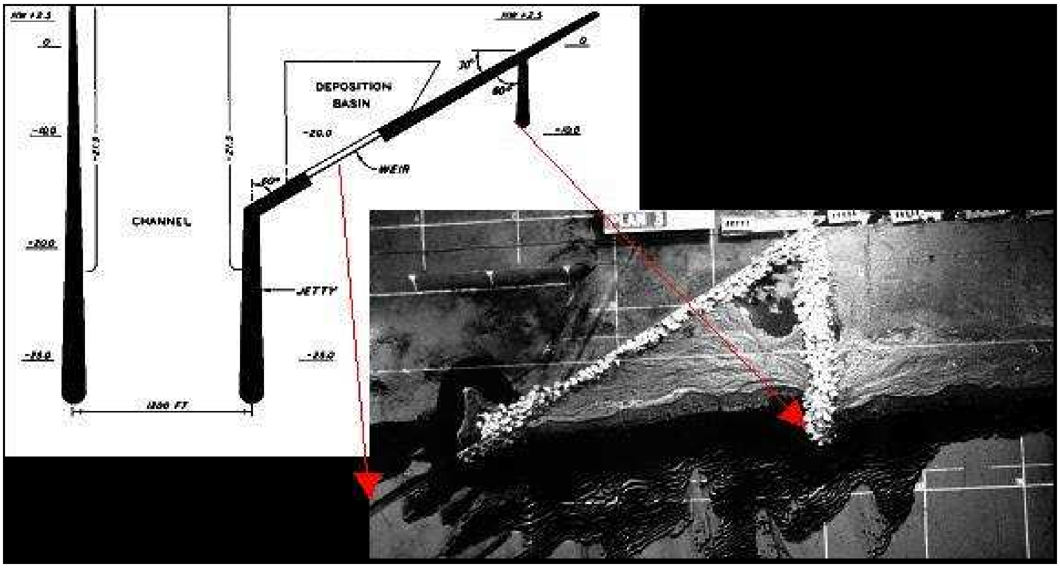


Fig. 12. Placement of a groin updrift of weir jetty to aid in capturing only net sediment volume in deposition basin.

systems to keep sediment reaching the shadow of the jetty, so that the sediment will be moved away from the jetty when wave direction changes.

Consideration of bypassing of sediment to the down-drift beaches should be part of a weir system. Regular dredging of the deposition basin can provide sediment for this bypassing. Such bypassing maintains continuity in sediment movement and integrity of the down-drift beach. Some natural bypassing around the jetty tip, especially during storms, is also expected. Planning of weirs, spurs, and groins is done as part of a sand-sharing system approach that involves means and costs for bypassing the appropriate volume of material, accounting for natural bypassing of sediment.

3.2.3. *Jetty weir construction material*

Jetty weirs have been constructed from concrete sheet piles, wooden piles, and rubble rock. Each of these materials can be placed to any required elevation after examination of the necessary considerations to determine height. The typical crest elevation range is between low water up to about mid-tide. Concrete and wooden piles can be set for a more precise elevation than rubble rock weirs. However, Murrells Inlet, with a rubble rock weir, functions well. The elevation of rubble rock weirs can be more easily adjusted later on, if necessary, than concrete or woodpile weirs. Also, wave reflection is less for rubble rock than for the sheet pile. Wave reflection may increase undesirable wave energy in the channel and may alter sediment pathways on the seaside of the weir as they approach the structure. Seabergh (1983), based on monochromatic wave model studies (which would tend to emphasize the effect), noted offshore movement of sediment before it reached the weir section due to the interaction of incident and reflected waves.

One other approach that would function as a weir, but offer greater wave protection is a highly permeable jetty. Over time, adding additional stone or removing stone might be placed to adjust permeability.

3.2.4. *Weir elevation*

Weir elevation is determined from a combination of leading parameters including tide range, wave height, inlet bay response (which will define timing of maximum ebb and flood flows with respect to tide elevation) and magnitude of left- and right-directed longshore sediment movement in the vicinity of weir.

The weir elevation must be such to allow sediment to pass over it and into the deposition basin. A low crest elevation would maximize sediment transmission by overtopping; however, wave energy would be relatively greater than if the weir were higher. Significant wave transmission would introduce wave energy into what is typically protected water for a regular jettied inlet. Multiple wave directions (incident and reflected) inside the entrance could be a hazard to navigation. Also the weir provides protection for dredging activity in the deposition basin and minimization

of downtime. Weggel (1981) describes wave transmission formulas to estimate wave height in the deposition basin.

Weir elevation with respect to inlet hydrodynamics is a subtle, but key parameter for the timing of maximum flows and flow volume over the weir. Inlets with a small bay tide range with respect to the ocean tide range have maximum currents in the inlet at high and low water. Therefore, the flood current would be strongest at high water, when wave energy would likely to be the greatest. A weir at an inlet such as this should be relatively higher than for an inlet that has a bay that nearly completely fills. If the inlet bay tide range is nearly as great as the ocean range, then maximum flood and ebb currents occur at mid-tide level. Probably the greatest care with respect to currents would be in regard to the direction of ebb flow. Presence of a strong ebb current directed towards the weir may cause a gradual cutting of the region between the deep deposition basin and the shallower water that separates the basin and the channel. Eventually, the channel might be pulled through the basin, causing a dispersal of sediments coming over the weir.

3.2.5. *Weir length*

Early weir designs called for long weir sections. This was thought necessary to prevent a storm from bringing in so much sand as to impound the weir and isolate it from the littoral system. To date, complications associated with storms have not been documented. As noted in the discussion on basin location, most of the sediment crosses over the weir at its intersection with the swash zone. For larger waves, some sediment is transported over the weir at the breaker line with the aid of flood tidal currents and longshore currents generated by breaking waves. If the breaker zone is located beyond the seaward limit of the weir, the sediment will likely be diverted along the outer portion of the jetty and enter the navigation channel as a tip shoal. Weir length is a tradeoff between wave protection in the channel and deposition basin area and the possibility of diverting significant amounts of sediment seaward. Local beach slope is also a factor in determining how far seaward the weir should extend. Flatter nearshore slopes require longer weirs to prevent too much sediment from bypassing the weir with a potential to enter the channel.

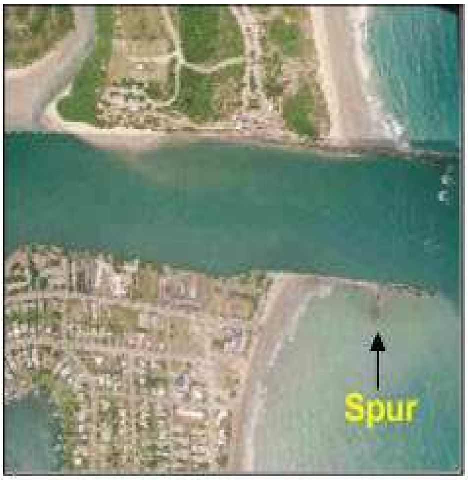
4. Spur Jetties

A jetty spur may be defined as a relatively short structure added to a jetty that flanks a navigation channel through an inlet. The spur will typically be nearly perpendicular to the jetty, but may be oriented at some angle with respect to the jetty in the range of 0 to 45 degrees. The spur may be added on the beachside of a jetty to prevent sediment from entering the inlet or may be placed on the channel side to divert the tidal current away from the jetty to reduce scour and possible jetty instability. This section discusses spurs placed on the beach or seaward side of a jetty.

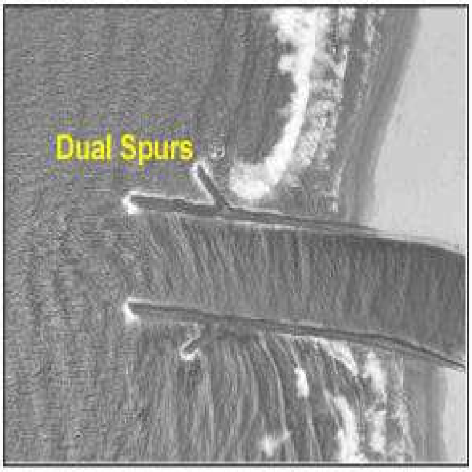
4.1. *Spur functioning*

A jetty spur can be constructed to reduce sediment from shoaling navigation channels at coastal inlets. The spur acts as a deflector of sediment-laden longshore currents developed from breaking waves, wind and tidal currents and actually functions as a deterrent to prevent sediment bypassing the jetty. Spurs are usually constructed of rock rubble similar to the adjacent jetty. The basic function of a spur is to alter the path of the sediment-laden longshore current and contain or divert the sediment,

(a)



(b)



(c)

(d)

Fig. 13. Examples of jetty spurs at (a) Bakers Haulover, Florida,(b) Fort Pierce, Florida, (c) Siuslaw River, Oregon, and (d) Shark River, New Jersey.

keeping it away from the navigation channel and possibly aiding its return to the beach system through re-diversion of the longshore current from going around the ends of the jetties to a 180° rotation of the current vector. Examples of jetty spurs in the United States are shown in Fig. 13. Table 2 summarizes the characteristics of these spurs with regard to length, angle with the jetty, and location along the length of the jetty. Typically, spurs are located about 75 % of the jetty length from the local shoreline. The Bakers Haulover jetty spur was placed at the end of the jetty.

Spurs also act as a breakwater and provide wave height reduction for the beach in its lee. If added to a weir-jetty system, it may provide wave reduction for dredging operations in the deposition basin. The spur may also reduce wave activity along the shore inside the weir near the basin. This would reduce spit migration towards the navigation channel. Another possible benefit for a new jetty system with spurs is that the outer tips of the jetties may not need to extend seaward as far as a system without a weir jetty, because seaward transport along the jetty is minimized (Bottin, 1981).

A spur jetty may also be included as part of a beach nourishment plan to aid in maintaining the sediments in the beach area (Walther and Dombrowski, 1999). A spur could be placed on a down-drift jetty as well as on the more typical up drift jetty if it was thought that the nourished down-drift beach might have a tendency to locally feed back along the down-coast jetty towards the navigation channel.

4.2. *Spur jetty design considerations*

Governing factors for spur design are location along the jetty, spur elevation, spur length, distance from the shore, beach slope, water depth, length, angle with structure, crest elevation, whether submerged or emergent, width of crest if submerged and wave climate.

4.2.1. *Spur location*

As noted from Table 2, existing spurs have been placed from about 60% of the jetty length from the shoreline to 100%, with 75% typical. This location will depend on local conditions near the jetty, such as bottom slope, wave climate, and proximity of the shoreline. These will determine where waves are breaking and where sediment transport will be greatest. For relatively short jetties or a flat bottom slope, wave breaking can occur seaward of a jetty system and sediment transport will be strongest in many cases at the location of the breaker. A spur may not function satisfactorily if this situation occurs frequently, as there is a small potential to intercept and divert sediment pathways.

Table 2. Spur jetty installations in United States.

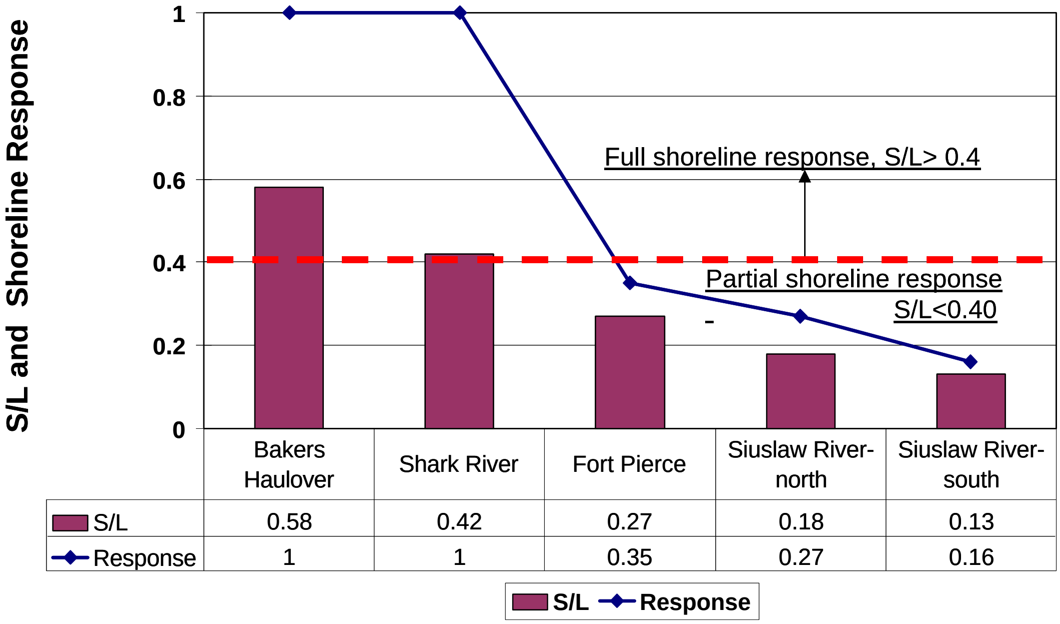
Location	Spur length, m	(1) Spur Distance from Local Average Shoreline, m (2) Length from Jetty Tip to Local Average Shoreline, m	Ratio of Spur Distance from Average Shoreline to Distance from Jetty Tip to Average Shoreline	Ratio of Spur Length to Spur Distance to Average Shoreline	Angle (deg) of Spur Relative to Jetty
Siuslaw river, OR	North jetty spur- 122 or 86 m $\perp$ to jetty	(1) 480 (2) 650	0.74	0.18	45
	Sourth jetty spur- 122 or 86 m $\perp$ to jetty	(1) 640 (2) 800	0.80	0.13	45
Shark river, NJ	North jetty spur- 50	(1) 120 (2) 160	0.75	0.42	90
Ft. Pierce Inlet, FL	South jetty spur- 60	(1) 220 (2) 350	0.63	0.27	90
Bakers Haulover Inlet, FL	North jetty spur- 35	(1) 60 (2) 60	1.00	0.58	90

4.2.2. *Spur elevation*

Spur elevation might be expected to be similar to the jetty to which it is attached. Dependent on wave climate, the spur can serve as a fishing platform if access is provided. The Fort Pierce spur provides an asphalt walkway. A long submerged spur has been proposed at Grays Harbor, Washington (Kraus and Arden, 2003). A reef-type spur was examined in the laboratory (discussed below) and may provide similar benefits as a surface-piercing spur, yet be less costly.

4.2.3. *Spur length*

A spur should be long enough to promote a diversion of flow from along the jetty to keep sediment in the nearshore area rather than move offshore towards the jetty tip. Some physical model results shown below will illustrate this. Field data from Table 2 were consulted to compose the plot in Fig. 14. An S/L ratio (S is spur length and L is distance from spur to the local average shoreline) is plotted for each field site. A shoreline response ratio was determined from the ratio of distance from the local average shoreline to the shoreline at the jetty divided by the distance from local average shoreline to the spur. Therefore, a shoreline response of 1.0 means the shoreline has reached the spur. This is seen for Bakers Haulover and Shark River, with S/L ratios greater than 0.4. The others have S/L less than 0.4 and shoreline responses much less than 1.0.



	Bakers Haulover	Shark River	Fort Pierce	Siuslaw River-north	Siuslaw River-south
S/L	0.58	0.42	0.27	0.18	0.13
Response	1	1	0.35	0.27	0.16

Fig. 14. Structure length (L) to distance from spur to local average shoreline (L) ratio plotted with the shoreline response, which is the ratio of (a) distance from the local average shoreline to the immediate shoreline at the jetty to (b) distance from local average shoreline to the spur.

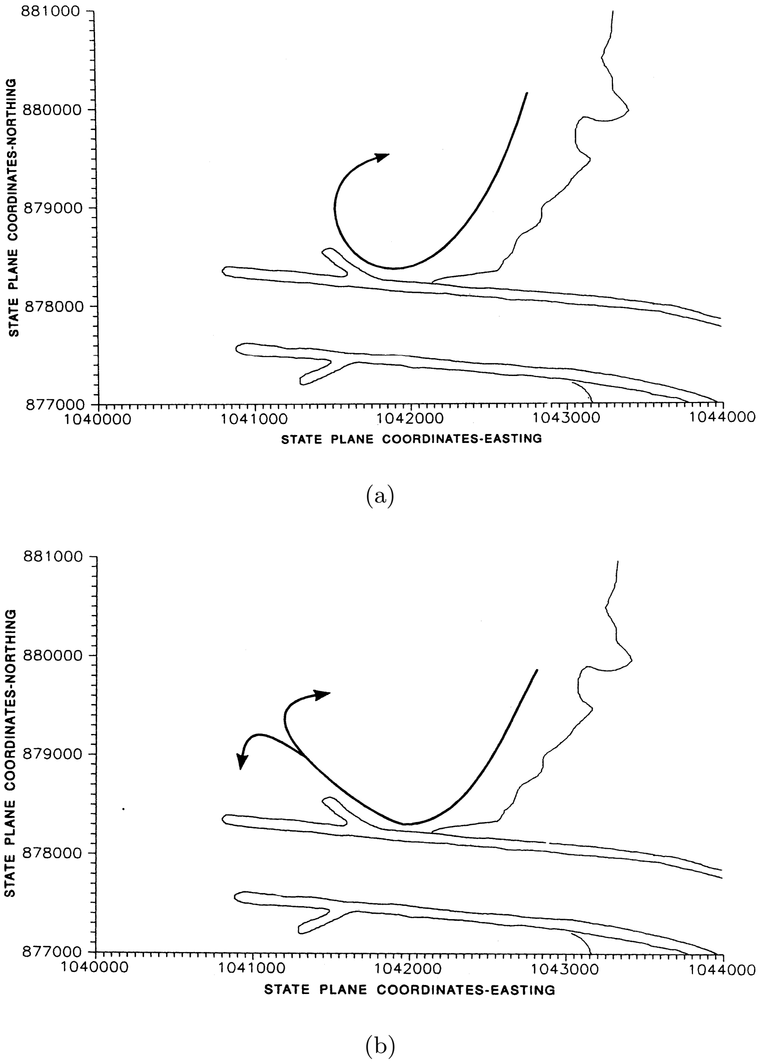


Fig. 15. Currents deflected by Siuslaw River, Oregon, jetty spurs (from Pollock, *et al.* 1995).

In this simplified approach that may neglect other important parameters, such as beach slope and wave height, a line was drawn at $S/L = 0.4$ to divide from full shoreline response and a partial shoreline response. Typically, one would not want the shoreline to reach the spur in order to keep the potential for sand transport to the seaside of the spur minimal. If the wave climate is not too energetic or if the spur is on the down-coast side of a jetty system where sediment is bypassed to, it might be acceptable. On the other hand, a sufficiently long enough spur is required to deflect the longshore current, as demonstrated in the physical model experiments discussed later.

4.3. *Physical modeling of spurs*

Monitoring study of the Siuslaw Inlet project by Pollock, *et al.* (1995) found good agreement with physical model predictions of Bottin (1981, 1983). The field monitoring indicated that, at high water, the flow patterns were circular eddies [Fig. 15(a)] and there was a strong seaward-flowing rip current along the jetty. At lower tide stages, and dependent on wave height, there might be an "*S*"-shaped flow pattern [Fig. 15(b)]. The results were similar in the physical model study. Based on this information, it may be noted that wave height, tide stage, and water depth are probably significant design parameters for determining the hydraulic response of spur jetties and most likely the sediment circulation response.

A study of spurs was initiated in the USACE Coastal Inlets Research Program physical inlet model (Seabergh, 2001). The physical model facility is a large experimental basin (46 m wide by 99 m long) with an idealized inlet and smooth offshore contours. Short-period waves and tidal currents can be simulated in this facility. A scale of 1:50 is applied to this generic inlet configuration. Twin parallel jetties were placed at the inlet entrance, with three spur conditions examined. Wave height, wave period, and tidal current were varied to produce different surf and along-shore-current conditions. Experiments included measurement of wave height, measurement of currents in the region on the seaside of the jetty with dye and acoustic-Doppler current meters, and examination of sediment pathways with a lightweight sediment tracer. Initial, or base, experiments collected data for the parallel jetty configuration.

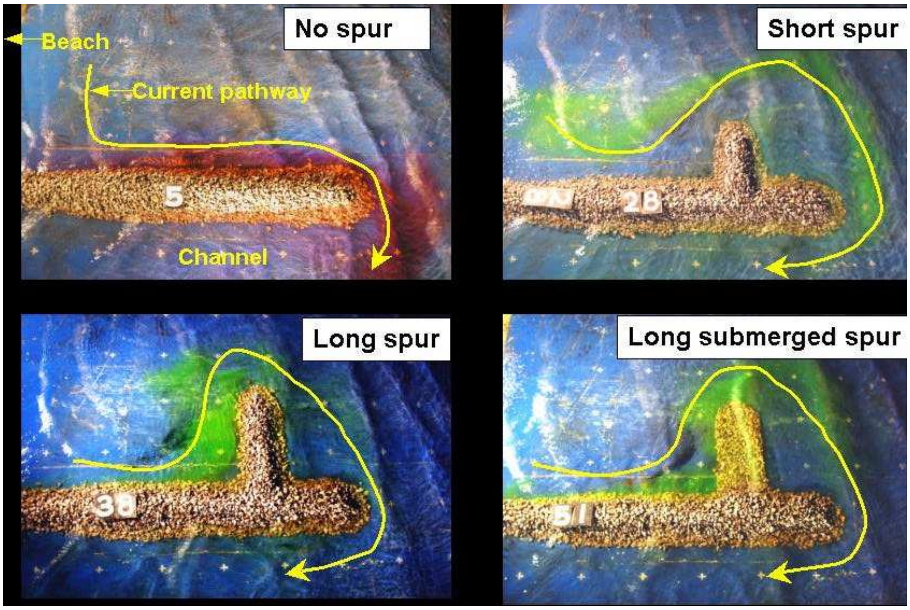


Fig. 16. Dye movement of wave-generated and tidal currents approaching jetty for a 2.4 m, 10 seconds wave and maximum flood current of 1.4 m/sec in channel. The arrow follows the path of the current.

A short spur was then constructed (46 m in length, if a 1:50 model to prototype scale is applied). A long spur of 76 m was also constructed and a submerged version of this long spur was made by reducing the crest elevation to mean low water while experiments were conducted at a +1.5 m elevation (again assuming a 1:50 model scale).

Figure 16 compares current patterns for these configurations. Red and green dye trace the current pattern created by breaking waves and a flood tide maximum current. The deflection of the current by the spurs is noted. The submerged spur also deflects the longshore current (bottom right, Fig. 16). Waves break on the submerged spur, effectively deflecting the longshore current and functioning similar to the emergent spur. A submerged spur is much less costly to construct than an emergent one and may have greater aesthetic appeal.

Figure 17 shows results of sediment tracer experiments for the same wave and tidal current conditions. The no-spur arrangement permits the tracer to enter the channel region. The short spur reduces this transport somewhat, but the longer spurs, including the submerged spur, achieve better results, holding sediment in the region of the shoreward side of the spur.

Figure 18 shows velocity fields in the region near the jetty for the four previously discussed model arrangements. An energetic wave (11 second period, 3 m height) plus a maximum flood current situation in the channel exist for these plots.

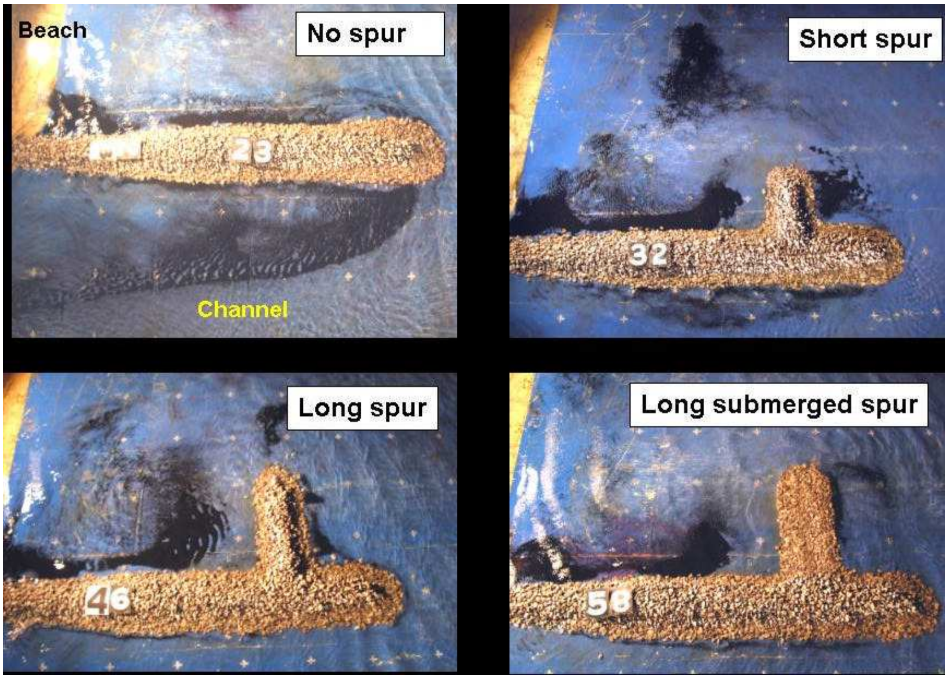


Fig. 17. Sediment tracer movement due to 3 m, 15 seconds waves, with maximum flood current of 1.4 m/sec in channel.

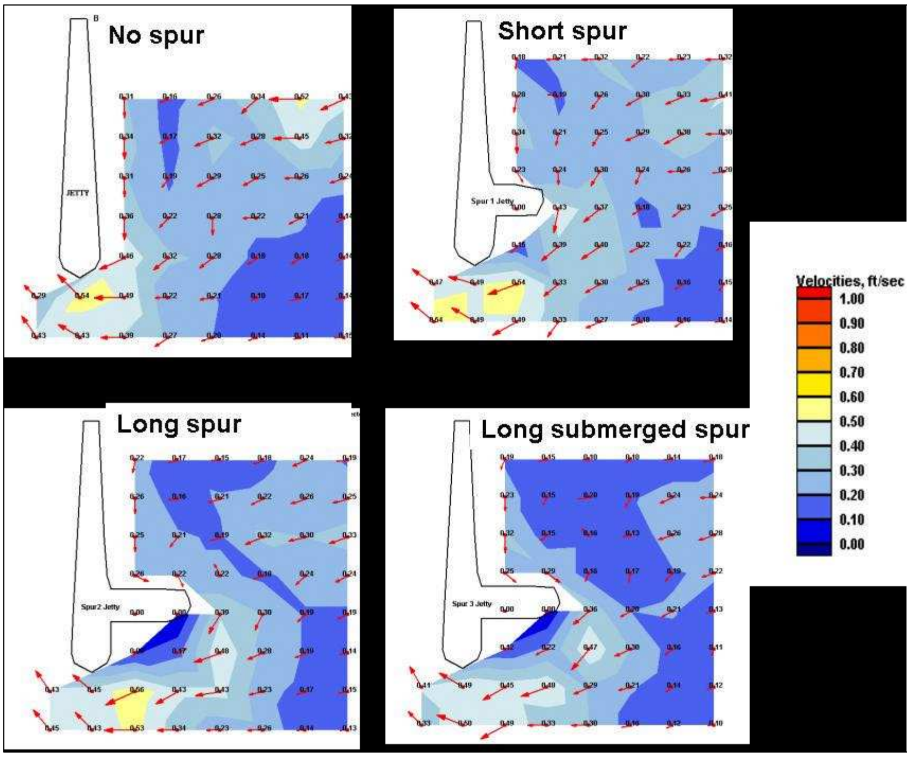


Fig. 18. Detailed velocity fields up-coast of dual jetties for 11 seconds, 3 m waves with maximum flood current in channel. Dark color contours are slower currents.

Interesting to note are the current deflections along the spurs and the increase in darker (weaker current) area regions, although changes are small.

5. Discussion and Conclusions

This paper has reviewed and updated information on sediment-bypassing methods for coastal inlets. Focus was placed on weir jetties and jetty spurs as constructive aids for directing sediment to facilitate sediment handling and reduce sediment transport into an inlet navigation channel. Such engineering works should be conducted with the intent of maintaining sediment bypassing between the beaches or shore adjacent to the inlet. Numerical modeling and physical modeling technology was described that can aid in the assessments of natural sediment bypassing and engineering actions to alter and complement natural bypassing.

Previous weir jetty projects were constructed with limited experience in their response to waves and currents. Examination of these projects shows that adjustments can be performed that should improve their functioning. Spit growth over the weir has resulted in unwanted bypassing of the deposition basin, causing navigation channel encroachment and shoaling. Simple changes to offset the basin relative to the weir edge or use of groins or sediment-training structures can prevent this. Weir

elevation is a sensitive factor for reducing wave activity in the inlet entrance channel and prevent migration of tidal currents through the deposition basin.

Jetty spurs are auxiliary structures that have potential for protecting deposition basins and reducing sediment movement towards the navigation channel located seaward of the jetty tips. They also reduce sand bypassing at an inlet by diverting sediment to locations away from the shadow of the jetty so that reversal of wave direction will move sediment back to its source region.

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